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All-optical switching of picosecond pulses in a GaAs quantum well waveguide coupler

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A time-resolved pump-probe configuration employing 10 ps laser pulses has been used to investigate the all-optical switching characteristics of zero-gap directional couplers containing a single quantum well. All-optical switching of the weak probe pulses from one port into the adjacent one was obtained at pump input pulse energies of 150 pJ. The switching takes place within the duration of the laser pump pulses. The recovery time of the device was found to be ~ 1.5 ns which indicates that carrier diffusion plays a major role in the device switching speed.

Recently great interest has been focused on the nonlinear directional coupler[1–5] because of its potential in optical fiber communications or chip-to-chip and on-chip optical interconnections. Fast modulation of a conventional nonlinear directional coupler using short optical pulses has already been reported.[6,7] In this letter, we report on the first all-optical switching of picosecond pulses in a directional coupler formed by the beating of the symmetric and antisymmetric modes of a wide strain-induced waveguide. Strain-induced single-mode optical waveguides have previously been used to demonstrate optical bistability.[8] Theoretical analyses of overmoded waveguided waveguide structures have been reported previously by Silberberg *et al.*[9,10] Such zero-gap directional couplers offer the advantage of a shorter critical coupling distance which could be important for future applications requiring photonic device integration.

The waveguide structure contained a single 100 Å GaAs quantum well which was sandwiched between two superlattices each with six periods of 15 Å GaAs and 15 Å $Ga_{0.7}Al_{0.3}As$. The remainder of the guiding layer consisted of a 0.5-μm-thick $Ga_{0.7}Al_{0.3}As$ layer on the top and a lower cladding layer of $Ga_{0.65}Al_{0.35}As$ 1 μm thick. The whole structure was grown by atmospheric pressure metalorganic vapor phase epitaxy (MOVPE) on a GaAs substrate. A 2000-Å-thick film of silicon nitride was deposited by plasma-enhanced chemical vapor deposition and stripes around 6–8 μm wide were subsequently delineated by photolithography followed by plasma etching, which selectively removed the nitride film only. The device was then cleaved to a length of 1 mm. The lateral waveguiding confinement was achieved through the straining of the semiconductor underneath the silicon nitride stripe, which resulted in an increase in refractive index owing to the photoelastic effect.[11] Although the mode structure of the waveguide thus formed was not accurately known, it was observed that the two lowest order modes could be supported underneath the stripe. The beating of these modes gave rise to a spatial intensity distribution, comprising two spots at the output facet of the waveguide coupler. The relative intensities of these two output spots are strongly dependent on the overall interaction length, the optical wavelength, and the lateral position of the input spot on the waveguide. As a rough model the guided modes of the coupler were calculated using a finite difference method, assuming that the region beneath the silicon nitride stripe has a refractive index 0.01 higher than the region outside of the stripe. It was estimated that the critical coupling length, L_c, of the structure was 256 μm.

The room-temperature photoluminescence spectrum of the layer revealed a main peak at 848 nm corresponding to the heavy hole exciton wavelength. In our experiments, the laser was operated at a wavelength around 855 nm and the corresponding absorption coefficient inside the quantum well itself was high. However, owing to the small overlap integral between the waveguide modes and the quantum well, the actual overall absorption constant of the waveguide was about 20 cm^{-1}. The photocarriers, which are created directly inside the well, gave rise to a large change in the refractive index there. The net overall nonlinear refractive index change was nevertheless still weak and for the 10 ps pulses used in the experiments, an energy per pulse of 130 pJ corresponding to a peak intensity of ~ 0.3 GW/cm^2, was required for all-optical switching.

The switching properties of the zero-gap directional coupler were investigated using a pump-probe configuration. A schematic diagram of the setup is shown in Fig. 1. A mode-locked frequency-doubled Nd:YAG laser running at 76 MHz, was used to synchronously pump a Styryl-9M dye laser which was cavity dumped to operate at 7.6 MHz. The vertically polarized 10 ps laser pulses were divided into pump and probe beams by a beam splitter. The probe beam was made to pass through a variable delay stage consisting of a fixed mirror and a retroreflector mounted on a computer-controlled stepper motor driven translation stage. The polarization of the pump beam was rotated through 90° before being recombined with the chopped probe beam using another beamsplitter so that they traveled in a collinear path. They were then focused into the input cleaved facet of the waveguide coupler using a laser focusing lens. The output facet of the coupler was focused both on a charge-coupled device camera and onto a fine slit

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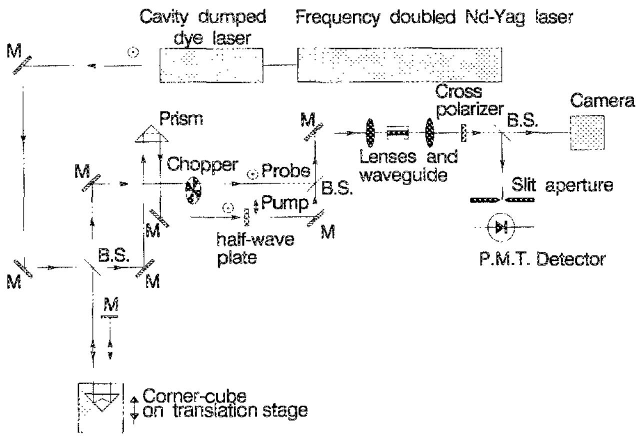

FIG. 1. Schematic drawing of setup for pump-probe measurements.

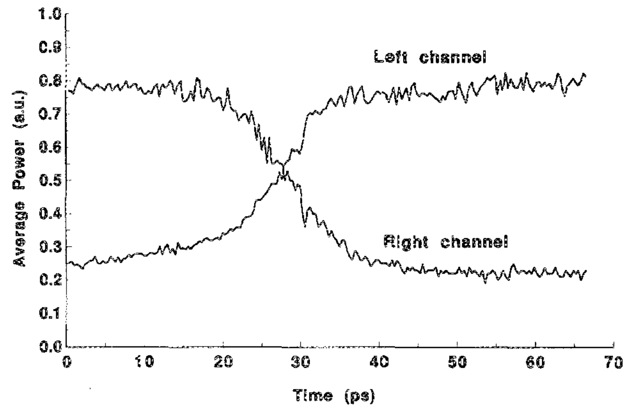

FIG. 3. Time-resolved switching of probe pulses.

with a photomultipler tube detector behind it. The detector was connected to a lock-in amplifier in order to monitor the chopped probe pulses emerging from either side of the coupler output. A cross-polarizer was used to block the pump beam so that the camera monitored only the probe signals.

With the pump beam completely blocked, the waveguide was excited such that the probe beam emerged mostly from the right side of the coupler. When the probe pulses arrived just before (~ 20 ps) the pump pulses, the probe beam remained on the right side of the waveguide [Fig. 2(a)]. However, when the probe delay was changed so that the probe pulses arrived slightly later than the pump pulses, the probe pulses were switched onto the left side of the output of the waveguide [Fig. 2(b)].

The probe delay was scanned in very small steps while the computer stored the lock-in amplifier signal corresponding to the average output power from either of the two output positions. First a scan was performed over a 67 ps delay variation between the corresponding pump and probe pulse. Figure 3 shows the signal being switched from one channel into the adjacent one within the laser pulse duration (~ 10 ps). The signal in the left channel was observed to rise while that in the right channel decreased.

By scanning the probe delay over 6.7 ns duration, the recovery time of the nonlinear coupler was obtained. Figure 4 shows the signal in both output channels being switched by the pump signal. The initial switch is followed by a slow recovery which obeys an exponential decay with a time constant of 1.5 ns.

Because the mechanism for the all-optical switch is believed to be due to free-carrier effects near the absorption edge, the recovery time of the switch will therefore depend on either the *in situ* carrier recombination rate or the time taken by the carriers to escape from the waveguide region. Our measurements show that the recovery time follows an exponential decay with a time constant of 1.5 ns. Since the carrier recombination lifetime of similar structures grown in the same MOVPE reactor measured by time-resolved photoluminescence and bleaching of the excitons in the absorption spectrum were 5 ns or longer, this leads to the conclusion that the lateral carrier diffusion is mainly responsible for the observed recovery rate. The sideways carrier diffusion can be modeled using a one-dimensional rate equation as follows:

$$D^*\nabla^2(\Delta N)=\Delta N/\tau, \tag{1}$$

where D^* is the ambipolar diffusion coefficient of the electrons in the quantum well structure, ΔN is the net free-carrier concentration, and τ is the decay time constant.

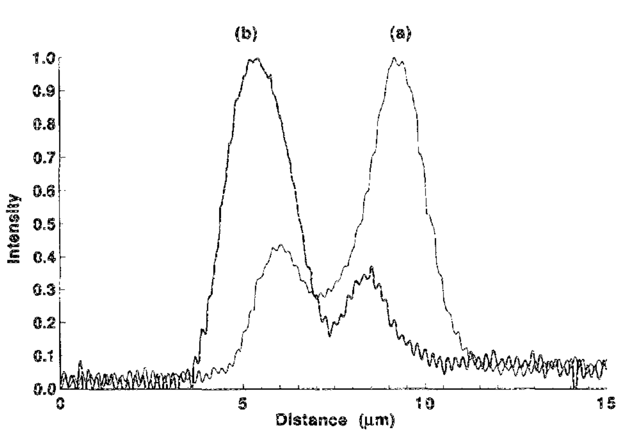

FIG. 2. TV line scans of the emerging probe pulses: (a) probe pulses arriving before pump pulses; (b) probe pulses arriving 33 ps after pump pulses.

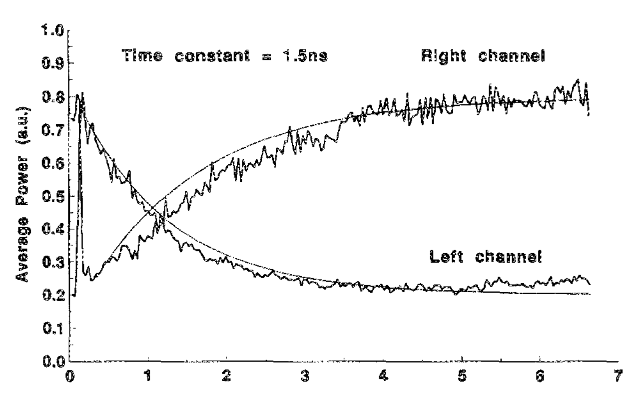

FIG. 4. Recovery time of the device after the initial switch.

The carrier concentration as a function of distance x, from the center of the spot of radius r_0 is given by

$$\Delta N(x) = \Delta N_0 \exp(-x/r_0)\exp(-t/\tau). \tag{2}$$

By substituting Eq. (2) into Eq. (1), we obtain

$$\tau = r_0^2/D^*. \tag{3}$$

Using a measured[12] value for the in well ambipolar diffusion coefficient $D^* = 16\ \mathrm{cm}^2/\mathrm{s}$ and assuming a spot size of 1.5 μm, a value of 1.4 ns is obtained for the decay time, in good agreement with our observations.

In conclusion, a directional coupler formed by the beating of modes in a wide waveguide containing a single GaAs quantum well has been shown to exhibit good all-optical switching characteristics. The switch-up time which depends on the speed of free-carrier generation is inherently fast and in our case this was limited by the pulse width of the laser.

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